A DIGITAL SCENE MATCHING TECHNIQUE FOR GEOMETRIC IMAGE CORRECTION AND AUTONOMOUS NAVIGATION

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ABSTRACT

A technique will be described for precise registration of two images of the same area, taken under different conditions. The images may differ in scale, orientation, or aspect angle, they may have limited distortion, or they may be obtained from different sensors, or from maps. The technique, called AUTO-MATCH, involves digital preprocessing of the images to extract edge contours, followed by a correlation of corresponding edge end points. The availability of an array of endpoints makes possible subpixel registration accuracy.

The technique is being applied to a system for assessment of geometric image quality (GIQAS), to be installed at NASA-Goddard later this year. This system will measure the registration vectors over an array of window pairs from Landsat images, so as to determine the distortion between them. Similar measurements could be used to infer relative positioning of the spacecraft. The GIQAS system accuracy is specified at 0.2 pixels.

The technique has also been considered for updating the inertial navigation systems of missiles or aircraft. Scene matching between an image obtained aboard the vehicle and a stored reference can eliminate the drift of an inertial platform. In order to demonstrate this capability in real time, Westinghouse has assembled a laboratory demonstration of AUTO-MATCH, which will be described.

INTRODUCTION

A digital scene matching technique will be described which performs precise registration between images under a variety of conditions. This capability can be used for geometric image correction, or for autonomous navigation of a vehicle with respect to terrain signatures. The technique involves two steps. First, the images are digitally preprocessed to extract edges. This is performed on a line-by-line basis in the images to achieve megapixel per second throughput rates. The edge end-points and its polarity (location of light and dark sides) are obtained, with a bandwidth compression of one or more orders of magnitude achieved. Second, edge end-points are compared between images. An algorithm is available which can perform registration between images independent of relative orientation, and of position and scale over wide ranges. Accuracy is possible to as low as 0.1 pixel depending on the available scene detail.

Details of the digital image processor will be described first, followed by a description of the registration operation. Application of the technique to the NASA GIQAS system (Geometric Image Quality Assessment System) will then be considered, as well as the problem of autonomous vehicle navigation.

DIGITAL IMAGE PREPROCESSOR

Image registration operations are accomplished by a hybrid digital image processor, consisting of a special-purpose preprocessor (to extract key image data) followed by a programmable general-purpose processor (to extract registration vectors). The function of the preprocessor is to extract the features required for registration computations from the gray level image samples. These features are straight-line contours of density gradient. In effect, the preprocessor produces a line drawing of the image. At the same time, the data bandwidth is reduced by one or two orders of magnitude, depending on the selected thresholds for minimum gradient detection and line length. In addition, the preprocessor routinely extracts statistics associated with a uniform matrix of image areas.

Operation of the preprocessor is on a line-by-line basis with respect to the input image. Therefore, video data may be handled directly. Furthermore, storage requirements in the preprocessor are limited to single lines of data only. The preprocessor comprises a series of shift registers. Data flow through the line extraction portion of the preprocessor is shown in Figure 1.

We will demonstrate the individual preprocessor operations with the use of Landsat images 1703-17590 (Reel 2) and 1739-17575 (Reel 2) representing location N 36 deg, W 120 deg (near Fresno, California) on June 26, 1974, and August 1, 1974, respectively. Portions of these images (MSS Band 4) are displayed in Figure 2. In particular, we will concern ourselves with the windows A and A', measuring 125 x 125 pixels in size. Gray level density values for these two areas are shown by Figure 3. The numbers represent the density to the nearest of 16 levels. Numbers above 9 are indicated with an overprinted "/". Large numbers represent dark areas.

Before preprocessing the images for line extraction, spatial filtering operations may be performed on the gray level data for purposes of noise smoothing or equalization of resolution in both dimensions.

To generate the straight-line contours (subsets) of the image, it is first necessary to compute the two-dimensional gradient (derivative) at each image point. This is done with a four-pixel window, which scans across the image in a raster format. The gradient direction (0 to 360 degrees) is quantized to one of 16 discrete directions. To suppress the areas of negligible gradient activity (containing no significant contour or edge information), a threshold is applied to the gradient amplitude. Gradients with amplitudes less than the threshold are set at 0. A display of gradient directions for windows A and A' in Figure 2 is shown in Figure 4. The numbers indicate direction from light to dark, (1 is from left to right). Numbers above 9 are overprinted with a "/".

After gradient thresholding, the edges are generally still too wide for subset generation. Therefore, a gradient thinning operation is performed that basically "skeletonizes" wide edges.

The algorithm uses a raster scanning window containing a gradient cell, X, and four of its nearest neighbors. The neighbors with colinear gradient directions are compared to X. The largest gradient amplitude is then retained. This procedure is repeated sequentially for each gradient point in the image. The maximized gradient display for images A and A' is shown by Figure 5. Compare this with Figure 4.

Edge generation is accomplished by "growing" a line formed by adjacent parallel gradients. As before, a 5-cell scanning window is employed. The new data point is labeled cell X. Its four neighbors are examined to find those containing a parallel (within a tolerance) gradient direction. If one is found, then the neighbor is dropped as a line endpoint, and X becomes the new endpoint. Neighbors that are colinear to the gradient of X are excluded to prevent false lines from forming.

The edges derived from images A and A' are shown in the graphical plots in Figure 6. They are numbered consecutively according to their lowest position on the plots. The polarity (location of light and dark sides) for each edge is coded by the presence or absence of stars at both ends. In general, the absence of the star indicates a change from light to dark in the clockwise direction, for an axis of rotation about the uppermost endpoint. For horizontal edges, the axis of rotation is placed at the right end of the subset.

A second preprocessor function is the collection of statistics over a matrix of square image areas. The measurements amount to a textural analysis of thewindows. They include histograms of gray density, gradient amplitude and direction, and subset length. Average values for gray density and gradient amplitude are also computed.

INITIAL ACQUISITION

The Westinghouse AUTO-MATCH techniques can achieve registration between two line-by-line scanned images of the same area totally independent of relative orientation and independent of position and scale over reasonable ranges. The registration output includes a measure of image similarity between the images, their relative scale and orientation, and the transformation of points between images. These steps are carried out in the sequence shown in Figure 7.

With reference to Figure 7, video signals from both images are digitized and preprocessed to extract image density contours or edges, as described earlier. The edges are defined by their endpoints. Features are formed from the edges that consist of the geometric relationships between pairs of edges and provide properties that are invariant, regardless of relative position, orientation, or scale. For example, these properties can include the relative angles between edges. These features are compared between images, with the initial result being a measure of similarity associated with the registration, as well as a measure of their relative orientation and scale. When the similarity match has been accomplished, endpoints on the corresponding contours in the images can be related. In particular, the center point of one image can be located on the second image.

The computations associated with a pair of subsets are listed in Figure 8. Edges AB and CD in image A correspond to A'B' and C'D' in image 8. A geometric feature is formed between the pairs by connecting endpoints A and C and A' and C'. The angles between the subsets and the connecting lines, γ_1, γ_2, and γ'_1 and γ'_2 will be equal if figures ABDC and A'B'D'C' are similar. Furthermore, their values are invariant with translation, scale, and orientation of these figures in the plane. Accordingly, these angles are the first elements in the geometric features used to achieve automatic acquisition. Along with these angles, the features also include the orientation, ϕ, ϕ', of the connecting lines relative to a reference axis in the image, and the lengths, S and S', of the connecting lines. They also include the edge endpoints.

Initial acquisition is obtained by matching pairs of features between the images with respect to γ, and by clustering the results with respect to relative orientation and relative scale. If the two images are identical except for translation, rotation, and scale, all the features will cluster at a point. If they have relative distortion, the cluster will be dispersed. The amount of acceptable distortion is controlled by an adjustable threshold.

The center of the cluster provides values for the relative orientation and scale of the two images. These values may be used to determine a transformation between the x and y coordinates for the two images. Since corresponding features contain endpoint coordinates, each pair can be used to calculate the nominal coordinates of translation, x_0, y_0, between the images.

These are again clustered to obtain an average over the images, and to eliminate anomalies caused by symmetrical figures such as rectangles. The cluster center in the x_o, y_o plane is used with the ϕ, S values to complete the final transformation from any point in image B to the corresponding point in image A.

Where correction for image warp is desired registration is carried out on a matrix of windows having sufficient density to accommodate the warp function.

PRECISION REGISTRATION

In the event that relative orientation and scale between the images are known, as is often the case, a much simpler computation is possible. In this alternate computation, a search is made in one image for a companion to the endpoint found in the other. The search is carried out over a window corresponding in size to the positional uncertainties between matching endpoints.

Either registration process differs from conventional point-by-point image correlation in several ways. First, only points of high information density (endpoints) are used in the computations; so, the processing load is greatly reduced. Second, since the positions of the endpoints are individually available, the average offset between the image pairs can be estimated directly. Finally, since density values are not used, multispectral or multisensor registration can be accomplished.

Registration operations that assume a prior knowledge of orientation and scale will be demonstrated on the pair of Landsat images in Figure 2. Preprocessor outputs for windows A and A' are given in Figure 6. The results obtained by stepping A against A' by 20 pixels in each direction are shown by Figures 9, 10, and 11. The match index contour of Figure 9 represents the number of matching endpoints at each location, divided by the number available for matching at the same location. Although it is similar to a correlation coefficient, it is used only for the approximate location of the match point. The precise location of the match point is obtained from the zero crossing point for the Δx and Δy contours of Figures 10 and 11. Each point on these contours is obtained from the average offset for the matching endpoints in the x and y directions. A transition from negative to positive values is obtained, somewhat like a discriminator characteristic.

Determination of the accuracy of the registration operation is based on the assumption that the uncertainty in the position of an endpoint, relative to its true position, is random. The uncertainty includes noise and quantization effects, and the characteristics of the preprocessor algorithm. If the average uncertainty is k' pixels, then the error for a window pair with n matching endpoints will be $k'\sqrt{n}$. In a test with 40 pairs of Landsat images, it was found that the average error was less than 0.2 pixels, and the value for k for the Landsat images is approximately 2 pixels.

GEOMETRIC IMAGE QUALITY ASSESSMENT SYSTEM (GIQAS)

The AUTO-MATCH technique is being applied to a system for assessment of geometric image quality, to be installed at NASA-Goddard later this year. The system will measure the registration vectors over an array of window pairs from LANDSAT images, so as to determine the distortion between them. A block diagram of the system, which will serve as one component of the Image Processing Facility (IPF), is shown by Figure 12. A real-time demonstration of registration performance, using a special-purpose preprocessor, is shown by Figure 13. The preprocessor is on the table at left. This unit provides data throughput rates up to 2.0 megapixels per second. Registration operations are carried out in the militarized minicomputer at center.

AUTONOMOUS NAVIGATION

The AUTO-MATCH technique could be used for precise autonomous navigation of spacecraft or aircraft in the manner shown by Figure 14. AUTO-MATCH makes use of a sensor on-board the vehicle, and provides update information to the vehicle navigation system. Reference data is obtained from previously sensed images or from ground operations. In either case, storage or transmission of the reference data can be accomplished with compressed bandwidth by first preprocessing the images.

Westinghouse completed a feasibility study of the navigation update capability of AUTO-MATCH for the Air Force Avionics Laboratories in 1977. (Final Report AFAL-TR-77-88). A side-looking radar was proposed for the on-board sensor. In order to simplify reference data base preparation, USGS airphotos were used without modification. As a result of this choice, edge polarization data could not be used, since the relative contrast at the edges in radar and airphotos differs. Samples of the images used in the study are given in Figure 15. Four image pairs were correctly registered from these samples, in spite of heavy shadowing in the radar image. Differences in orientation and scale between samples were removed by simple computations applied only to the preprocessed edges, based upon estimated values for these parameters. The estimated values would normally be obtained from the navigation system.

Performance statistics were obtained from a series of 58 radar/airphoto pairs covering mountainous and rural terrain, urban areas, and land-water combinations. For single image pairs, correct acquisition was obtained in about 90% of the samples. Fix reliability can be greatly improved by the use of the windows in redundant combinations. Fractional pixel position accuracy was also demonstrated on this same image set.

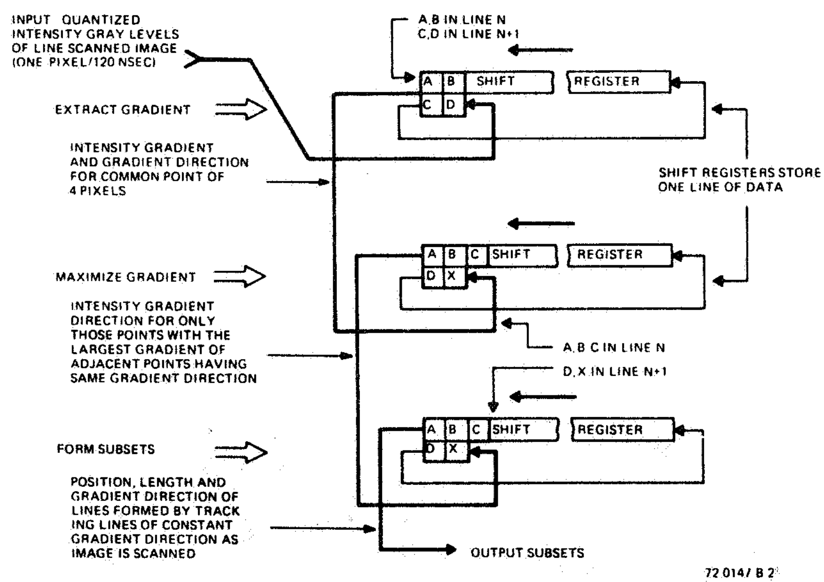


Figure 1. Flow of Data Through the Preprocessor

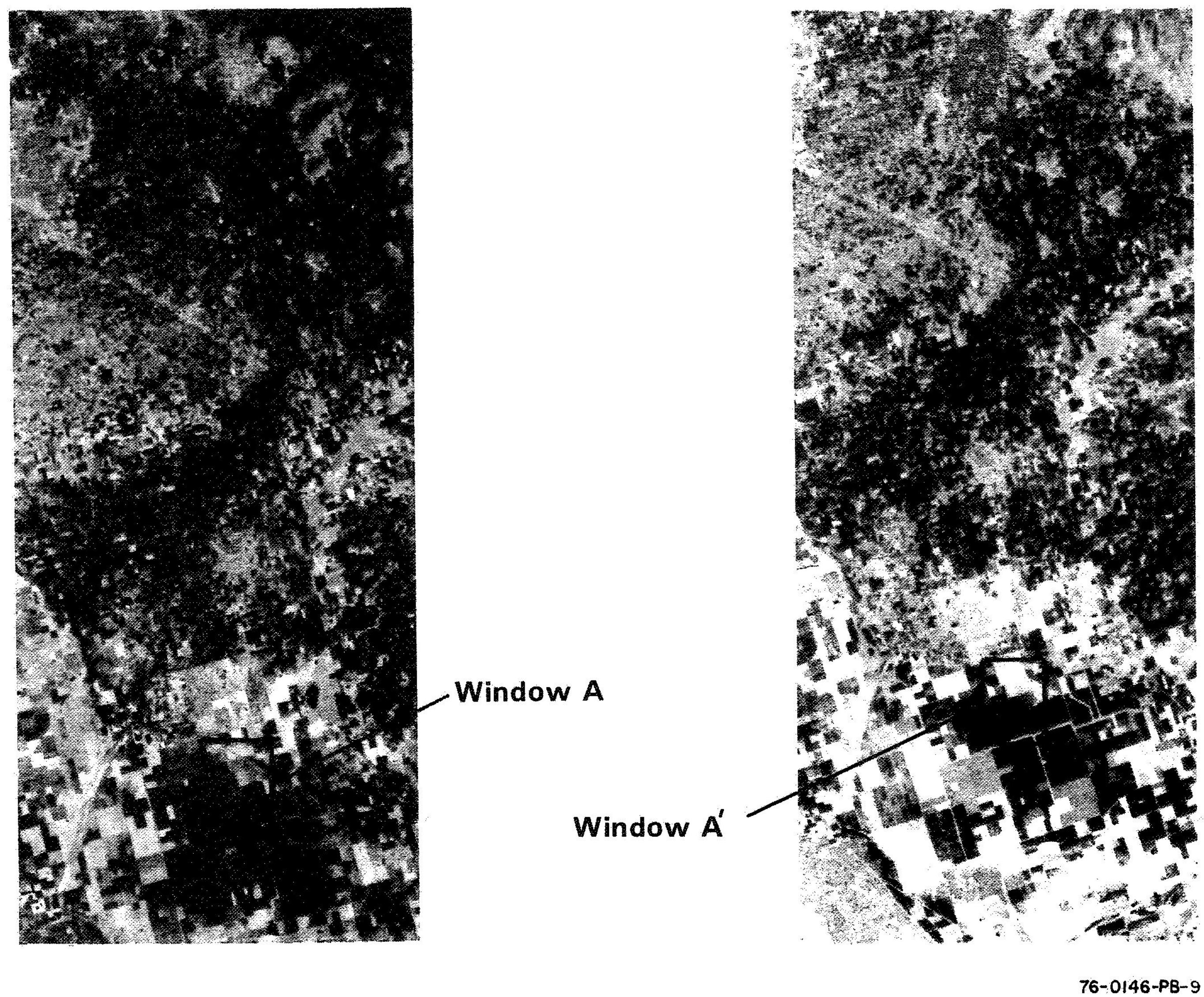
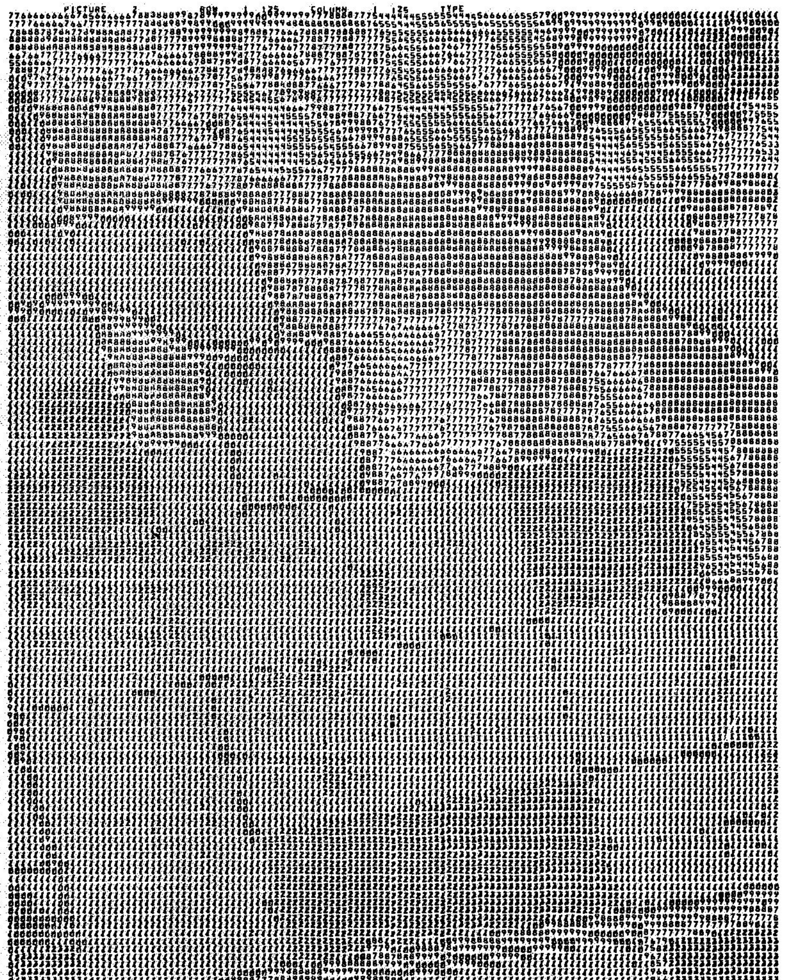
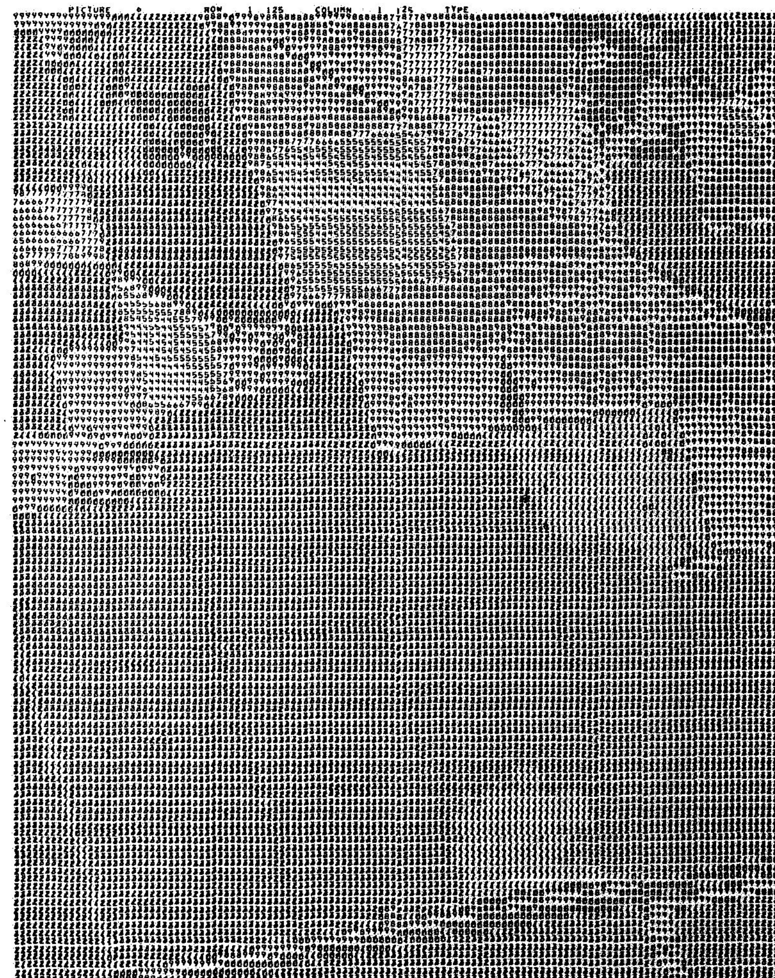


Figure 2. Portions of LANDSAT Images - (a) 1703-17590 and (b) 1739-17575 in the Vicinity of Fresno, California for June 26, 1974, and August 1, 1974, Respectively



Window A



Window A'

Figure 3. Gray Level Density Values for Windows A and A' in Figure 2

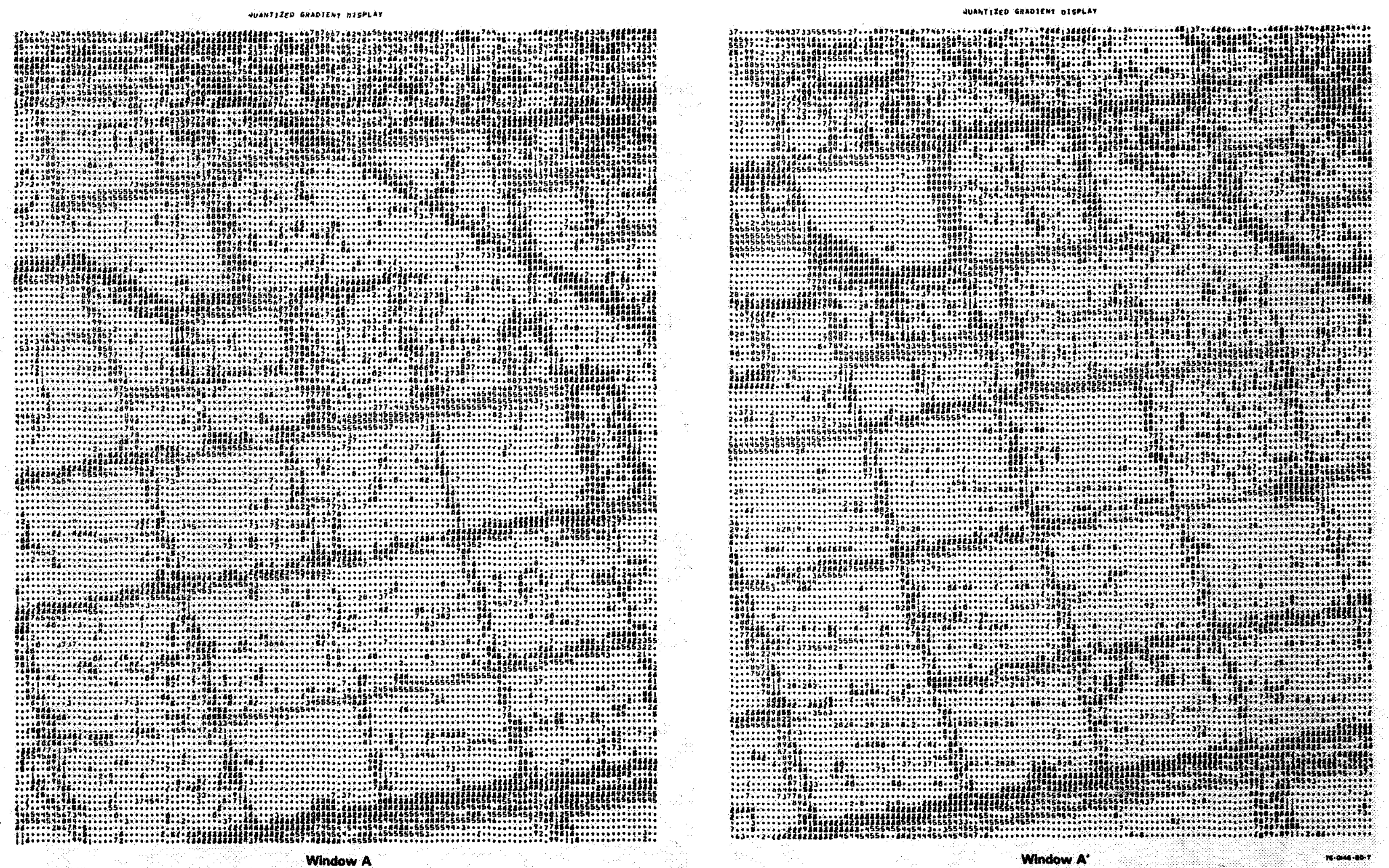


Figure 4. Gradient Directions for the Windows in Figure 2

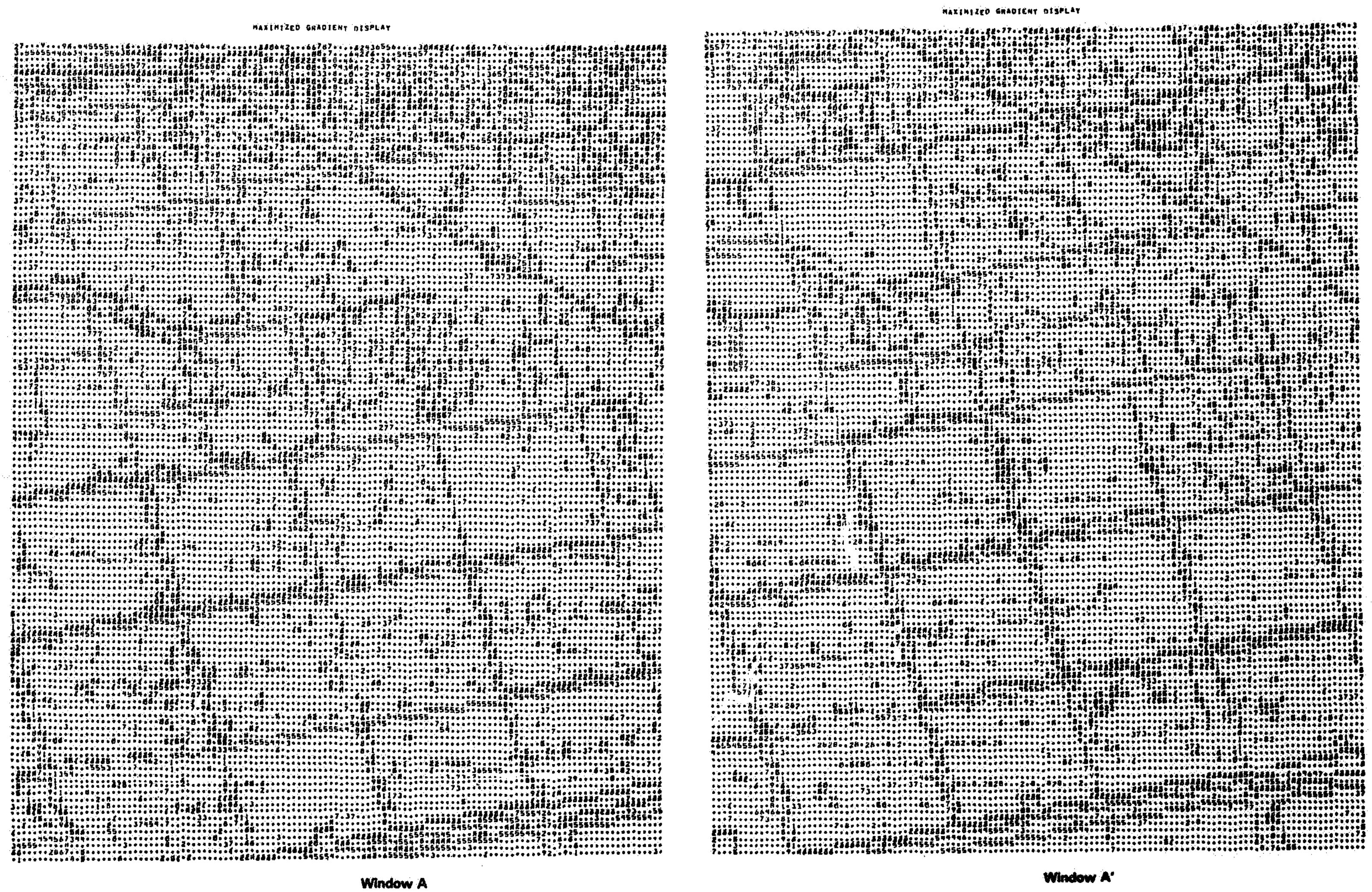


Figure 5. Maximized Gradients for the Windows in Figure 3.

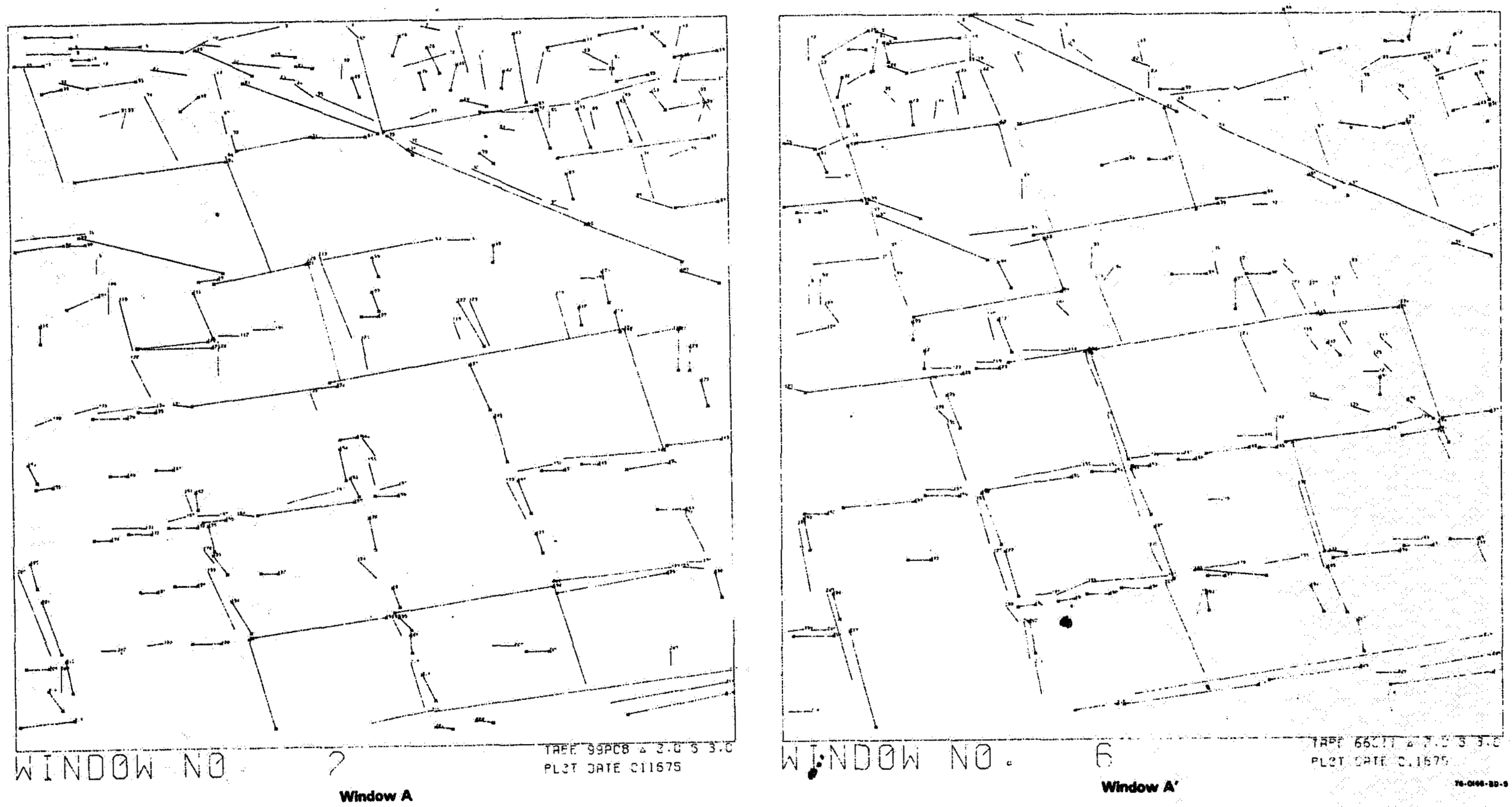


Figure 6. Line Contours (Subsets) for the Windows in Figure 2

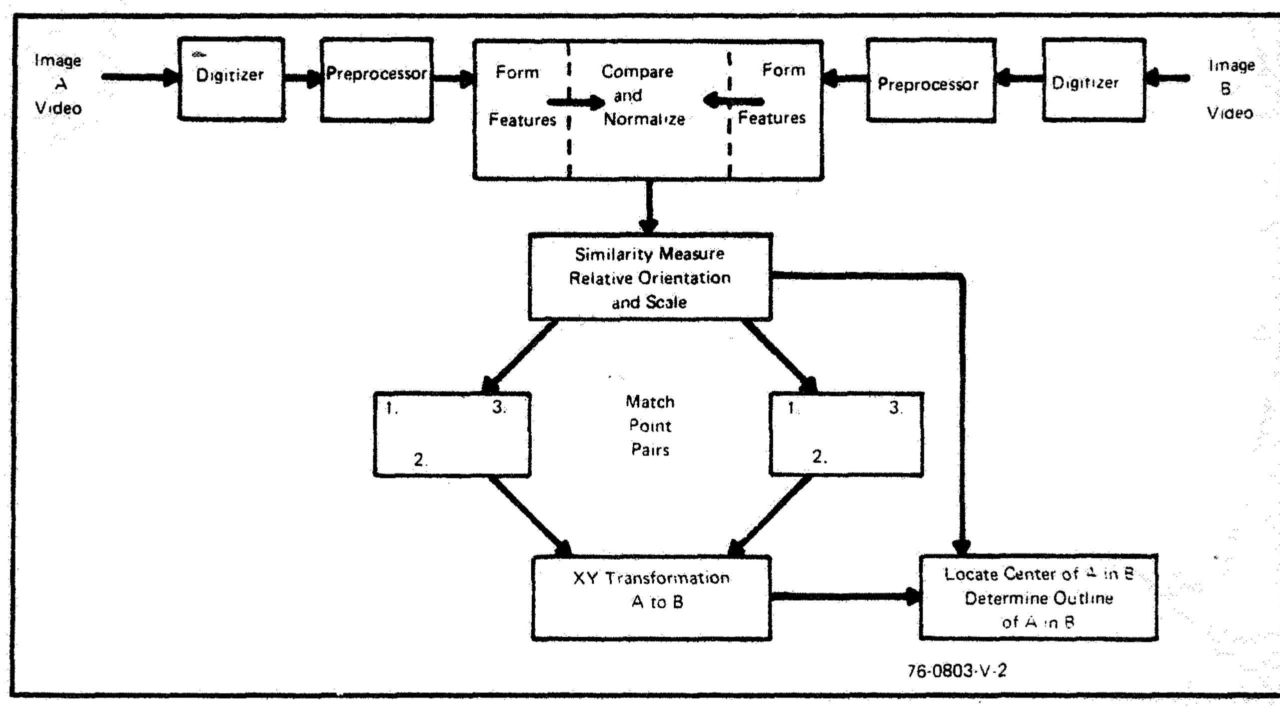


Figure 7. Registration Steps for Initial Acquisition

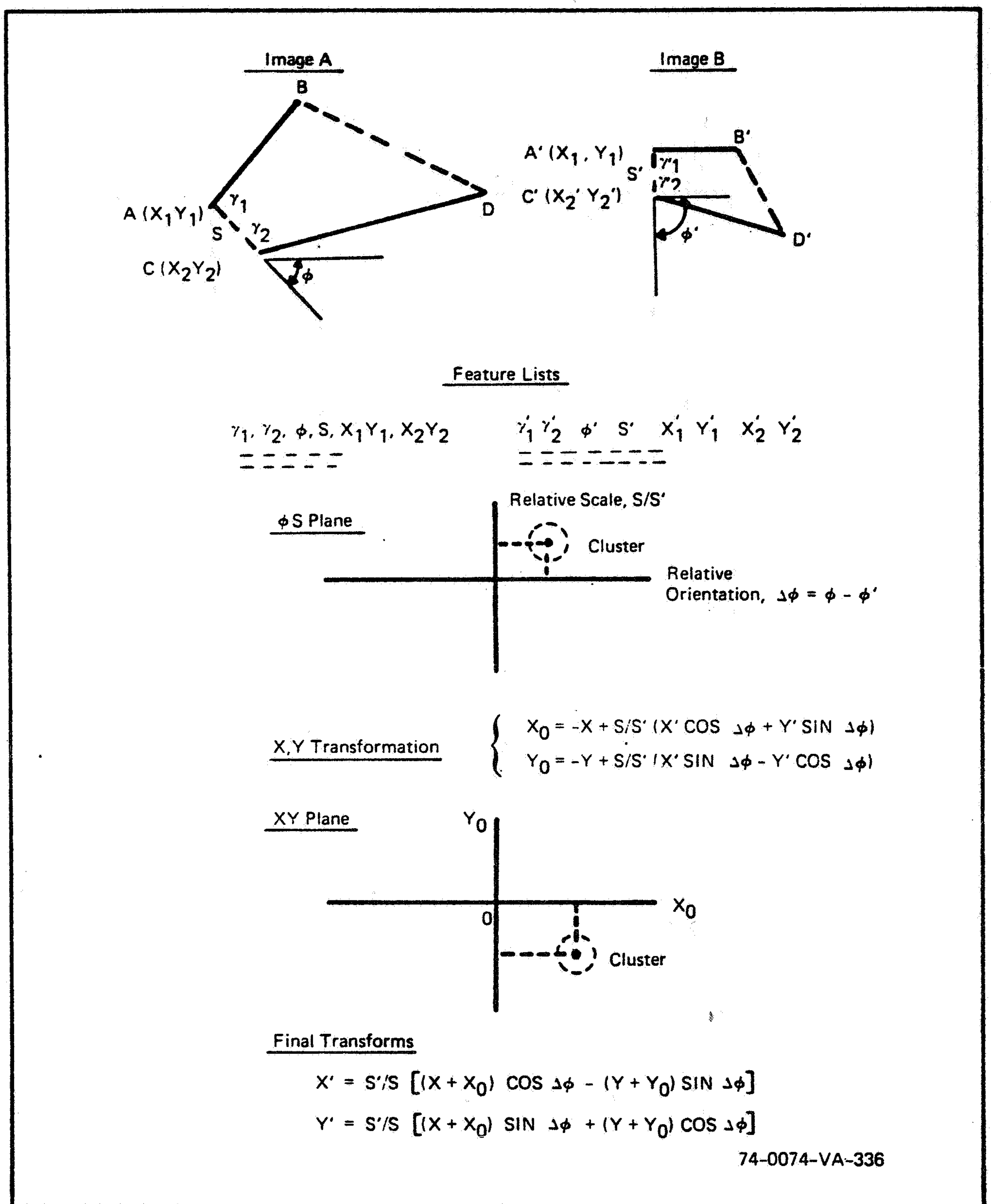


Figure 8. Computations in the General Case of Initial Acquisition between Images with Uncertainty of Position, Orientation, and Scale

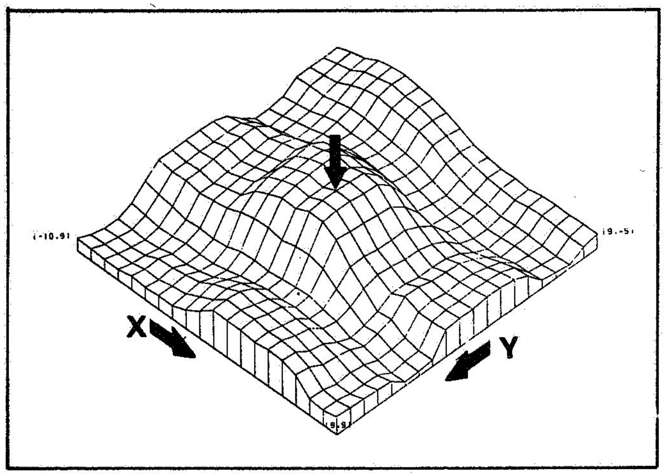


Figure 9 . Match Index Contour Obtained by Stepping Images A and A' of Figure 2

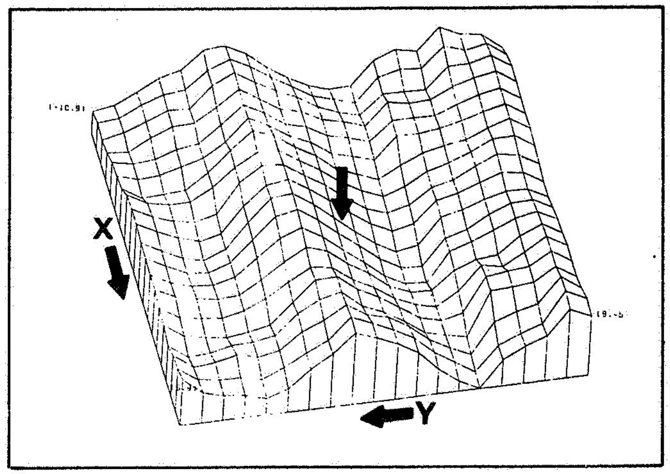


Figure 11. The ΔY Contour for Figure 9

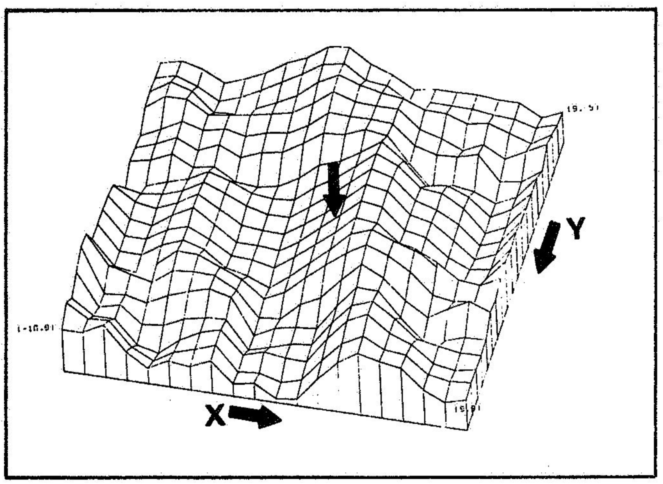


Figure 10. The ΔX Contour for Figure 9

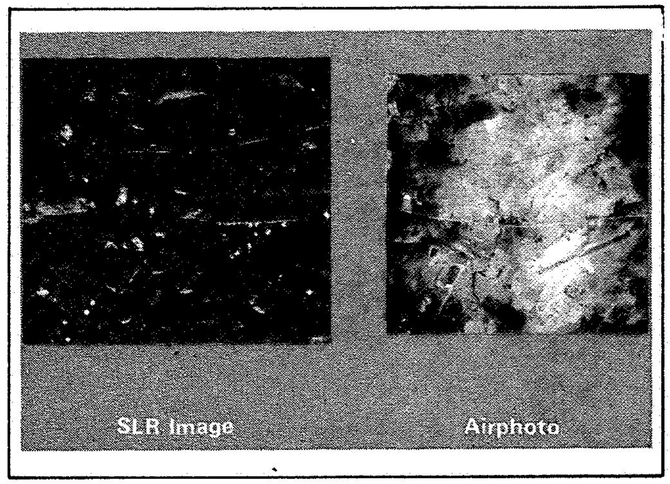


Figure 15. Images of the San Luis Obispo, CA, Area

Relationship of Hardware Components for Geometric Image Quality Assessment System

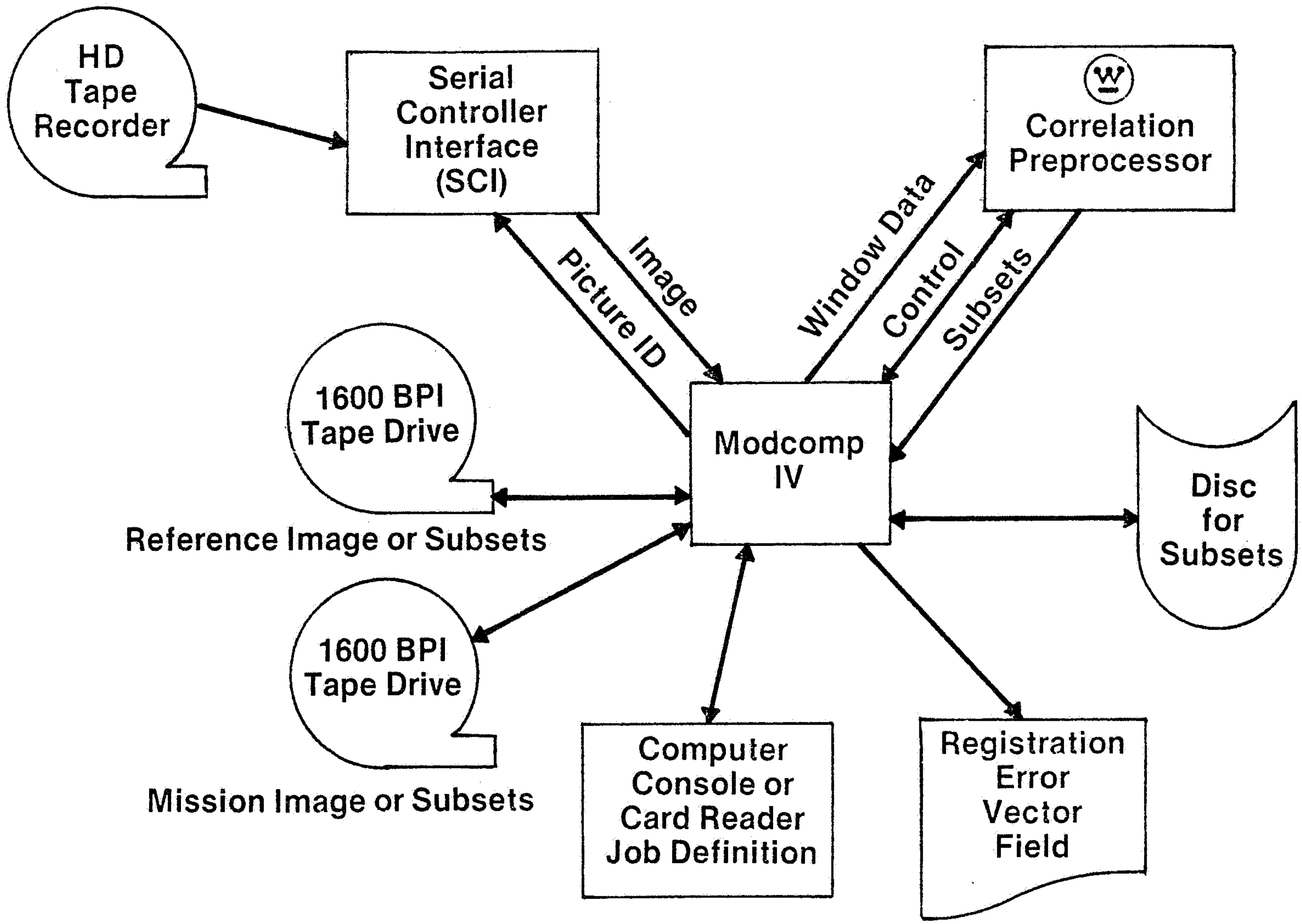


Figure 12.

78-0300-VB-6

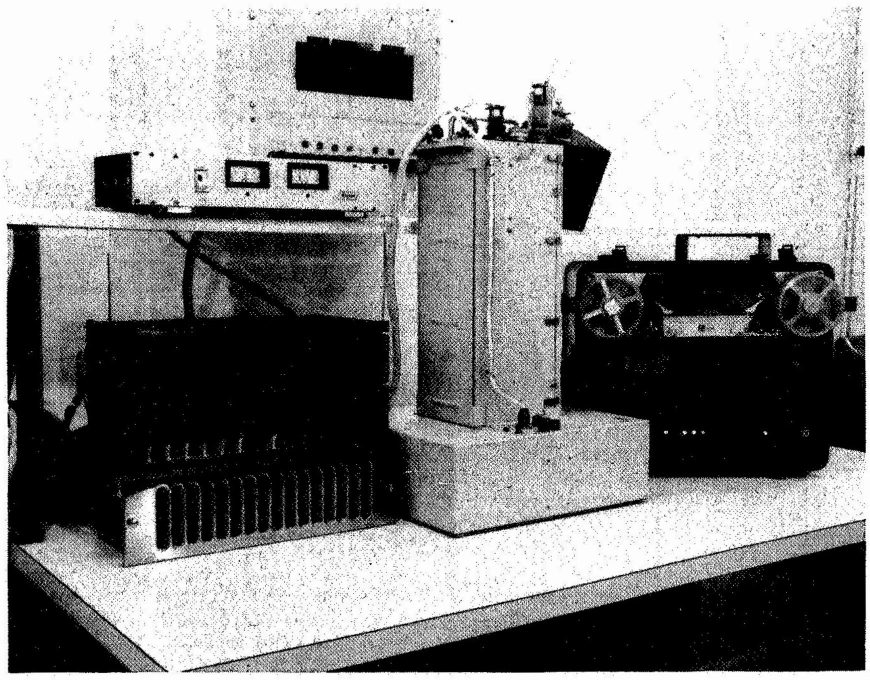


Figure 13. AUTO-MATCH Demonstration in the Westinghouse Image Processing Laboratory

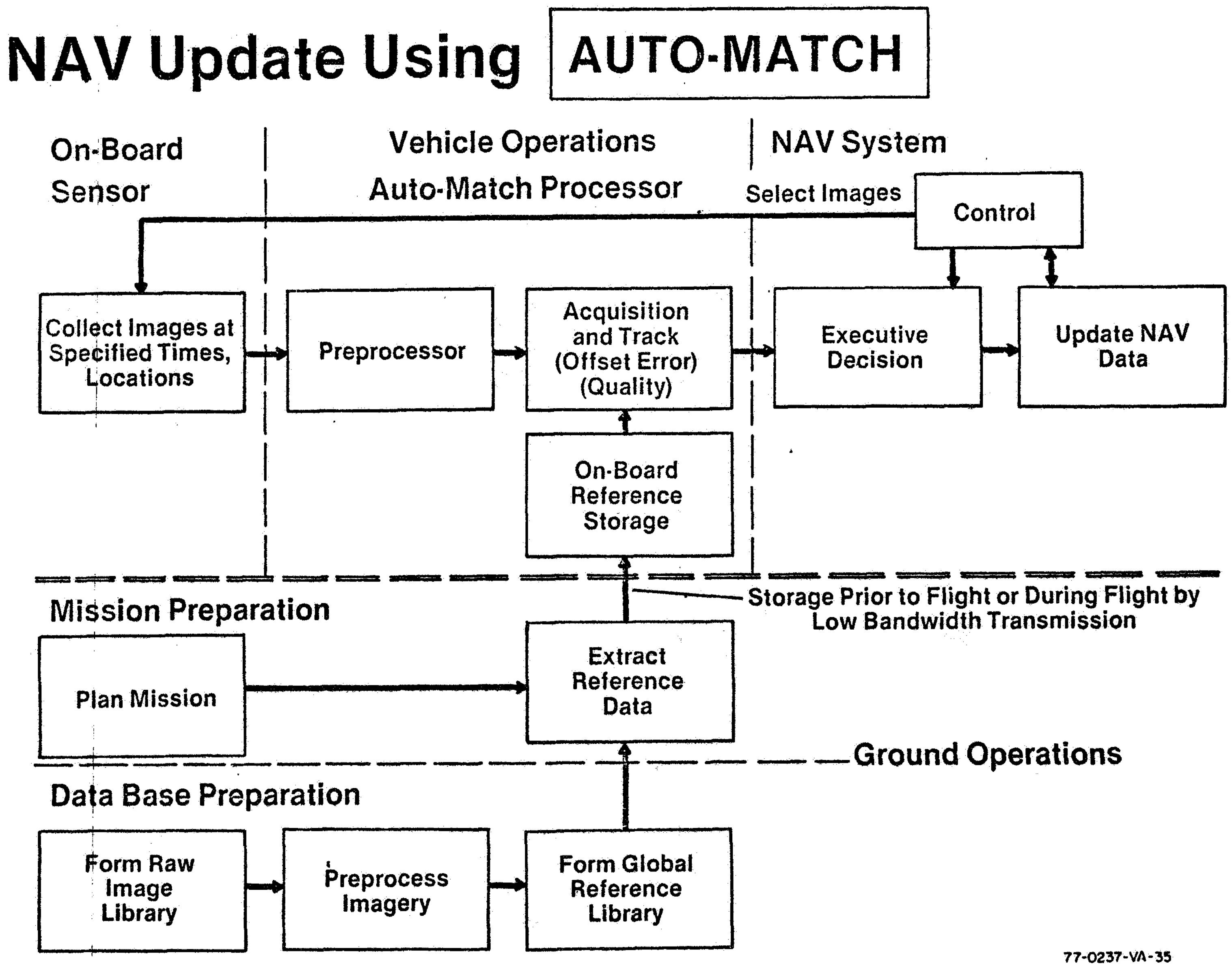

NAV Update Using
AUTO-MATCH
On-Board
Sensor
Vehicle Operations
Auto-Match Processor
NAV System
Select Images
Control
Collect Images at Specified Times, Locations
Preprocessor
Acquisition and Track (Offset Error) (Quality)
Executive Decision
Update NAV Data
On-Board Reference Storage
Storage Prior to Flight or During Flight by Low Bandwidth Transmission
Mission Preparation
Plan Mission
Extract Reference Data
Ground Operations
Data Base Preparation
Form Raw Image Library
Preprocess Imagery
Form Global Reference Library
77-0237-VA-35

Figure 14.